ECHO Annual Report 2015-2016

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Summary

The External Calibrator for Hydrogen Observatories (ECHO) is an ongoing project to develop precision calibration sources for low frequency radio arrays targeting highly redshifted 21cm radiation at cosmological distances. The first goal is to make **precision maps of the primary beams** of widefield arrays such as the Murchison Widefield Array and the **Hydrogen Epoch of Reionization Array**. The accuracy of existing beam maps have been found to be a key limiting factor in the data analysis steps. In the past two years we have gained proficiency with drone technology, designed and built a first functional system. We tested it extensively on a well known calibration element in Green Bank with overall very encouraging results. The testing also revealed the importance of frequent field testing and quick analysis of data. In the following months we developed a new version of the pipeline which provides results in real time and partnered with Embry Riddle in nearby Prescott Arizona which has set up several MWA tiles for pulsar research. We have obtained a **first map of the MWA tile** and plan to make several more over the summer, targeting publication in the fall. Embry-Riddle is working with us to build a HERA dish on the same site. We expect a first set of HERA beam maps before the end of the summer.

ECHO Overview

New arrays probing redshifted 21cm radiation from hydrogen gas in the early universe (e.g. PAPER, MWA, HERA, LOFAR, CHIME, Tienlai, etc) have high-precision performance requirements necessary to separate the cosmological background from the astrophysical foreground. Knowledge of the antenna beam has been identified in the literature as particularly critical information by comparing detailed instrumental simulations with data from first generation arrays. However, our knowledge of the antenna beams for these arrays is still quite limited. These arrays are all widefield transit arrays; they are fixed to the ground and unable to use the traditional method of scanning across a known source. The External Calibrator for Hydrogen Observatories (ECHO) is a dedicated program to address the missing beam information by making precision maps of antenna beams using drone-mounted calibration sources. The long-term goal is to make routine maps of as-built beams, mapping out antenna-to-antenna variation in-situ and feeding that information back into the data analysis.

MWA and HERA simulations by Thyagarajan, Jacobs, et al. (2015a and 2015b) have suggested that the primary limitation of current beam models/measurements is the precision of the map far from pointing center, as this is where the most spectral variation occurs. From these studies, we have identified a reasonable specification on the precision of a useful primary beam measurement for ECHO. ECHO should provide a map with 1% error at a beam amplitude of -45dB compared to the peak response. Depending on the array, the -45dB point may occur near the horizon.

Hardware implementation

The ECHO Platform

Following preliminary testing with scale models during the first year of the project, in Year 2 we have implemented the full-scale hardware platform with a quad-octo (8 propellers on 4 arms) UAV carrying a commercially available broadband antenna powered by a compact digital signal generator. Position and attitude is measured by a GPS, magnetometer, and accelerometer suite and is recorded by the UAV's on-board flight computer. The ECHO system is able to work with a variety of receivers connected to the antenna under test, but has been used so far most thoroughly with a commercially available software defined radio. Initial tests of the new system indicated that it exceeded the needed stability and repeatability.

Field Testing and Calibration

Initial Validation

We performed our first major test at Green Bank, WV in August 2015. This was the first test of the beam mapping operation on an antenna under test that had a beam pattern already known to high precision. The beam mapping system described by Neben et al. (2015) uses the ORBCOMM satellite constellation to map the primary beam of an antenna under test at a single frequency (139 MHz) by calibrating the satellite signal to a reference sleeved dipole. The reference dipole has a well defined primary beam, making it ideal to act as the antenna under test for our first calibration of the ECHO mapping process.

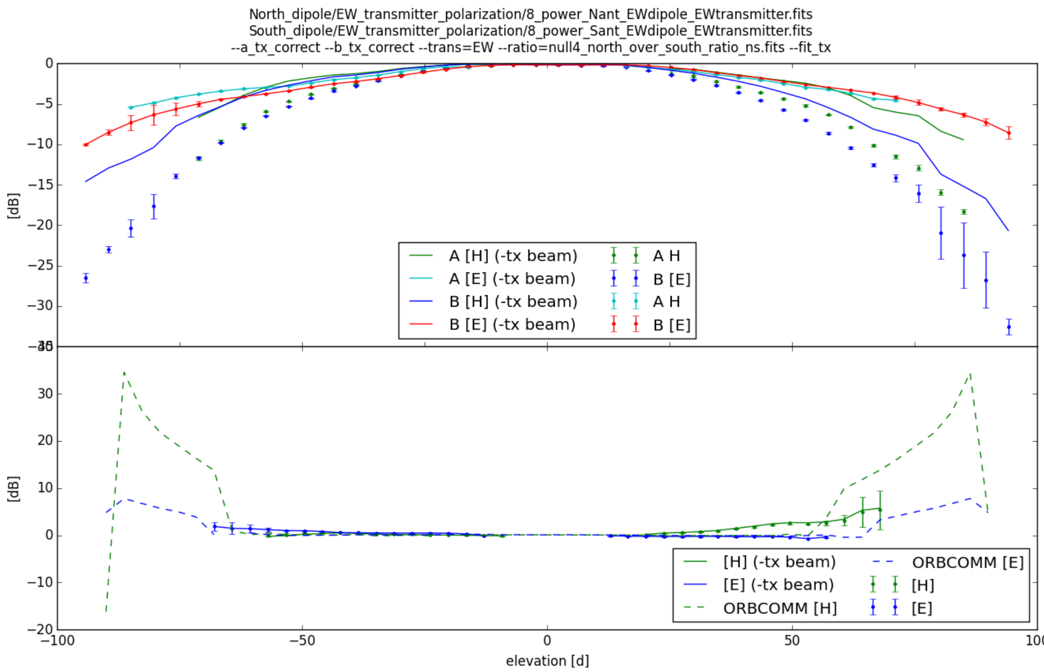


Figure 1: Results from Green Bank calibration testing. Maps of two identical dipoles agree to within a few percent across the beam. In places there is a systematic offset which is likely due to an unstable transmitter alignment.

The resulting maps (described in more detail by ECHO Memo #1) agreed with models to within a few percent across much of the beam.

While measurements in some maps displayed systematic biases at the few sigma level, the maps were able to get to much lower elevation than the matching satellite measurements which diverge significantly for beam levels of -15dB and lower.

The conclusion of this test was that the basic hardware setup and mapping process is sound but close attention must be paid towards systematics arising from mis-aligned antenna mountings and similar issues. Such systematics could be identified faster in the field if we could reduce the lag time between data collection and reduction into a beam map. Development was begun on a system which used the drone telemetry stream to produce beam maps in real time.

Systematics owing to mis-aligned transmitter antenna are of a family of errors in our understanding of the beam of the ECHO calibration source as mounted on the drone. Work has begun towards improving these by detailed electromagnetic modeling of the antenna/drone system using CST Microwave studio.

Partnership with Embry Riddle

Testing in Green Bank highlighted the value of testing in a well equipped site that is located in a comparatively sparsely populated area. In 2016, we undertook a search for a nearby testing location outside of the Phoenix area which fit these requirements. In April, we entered into a new collaboration with Embry Riddle Aeronautical University (ERAU), building on existing collaborations between ASU and ERAU, to use the ERAU radio observatory as a nearby test location.

The Embry Riddle Radio Observatory is located in Prescott, Arizona on the north side of the campus of Embry Riddle Aeronautical University. The Observatory has a number of radio systems for use by students for radio astronomy and aerospace training. Prof. Andri Gretarrson and other faculty already have a strong focus on the low radio frequencies, and have set up low frequency array elements cloned from MWA, LOFAR and LWA. Included among these are three MWA tiles, an LWA antenna, and a LOFAR low-band antenna. ASU and ERAU are collaborating on the addition of a HERA dish, which is currently under construction.

First Look at an MWA Antenna Tile

In May, we conducted our first flights at ERAU, focusing on site evaluation, but also performing a characterization of the new online system and making a first map of an MWA tile. The ERAU version of the MWA antenna tiles is identical to the actual tiles used at the telescope in Western Australia, using parts purchased from the same manufacturer, including LNAs and beamformers. The only exception is the addition of a nearby 7-foot tall chain link fence topped with barbed wire (see image at left) surrounding the site. Due to the proximity of the fence, the antenna beam of the tile as mapped by ECHO in May is expected to depart significantly from the precision models of MWA antenna tiles (Sutinjo et al 2014), however it should still display the expected general pattern of a primary beam surrounded by strong grating lobes. In upcoming tests, we plan to perform high-precision mapping with the fence removed.

MWA antenna tiles are 4x4 phased arrays of dipole “bowties” that sit on a flat ground-screen. The ERAU observatory has three MWA antenna tiles installed. The signals are fed back into the observatory building where the beamformers are commanded via a ipython interface. To make a map with ECHO we hooked up the ECHO receiver (a SignalHound BB60) to the East-West tile output available in the observatory control building. We flew a flight pattern with waypoints at healpix locations with nside=8, limiting the lower altitude limit to 60m. The transmitting dipole was kept locked to an EW orientation. The resulting beam map and cuts through the E- and H-planes are shown below.

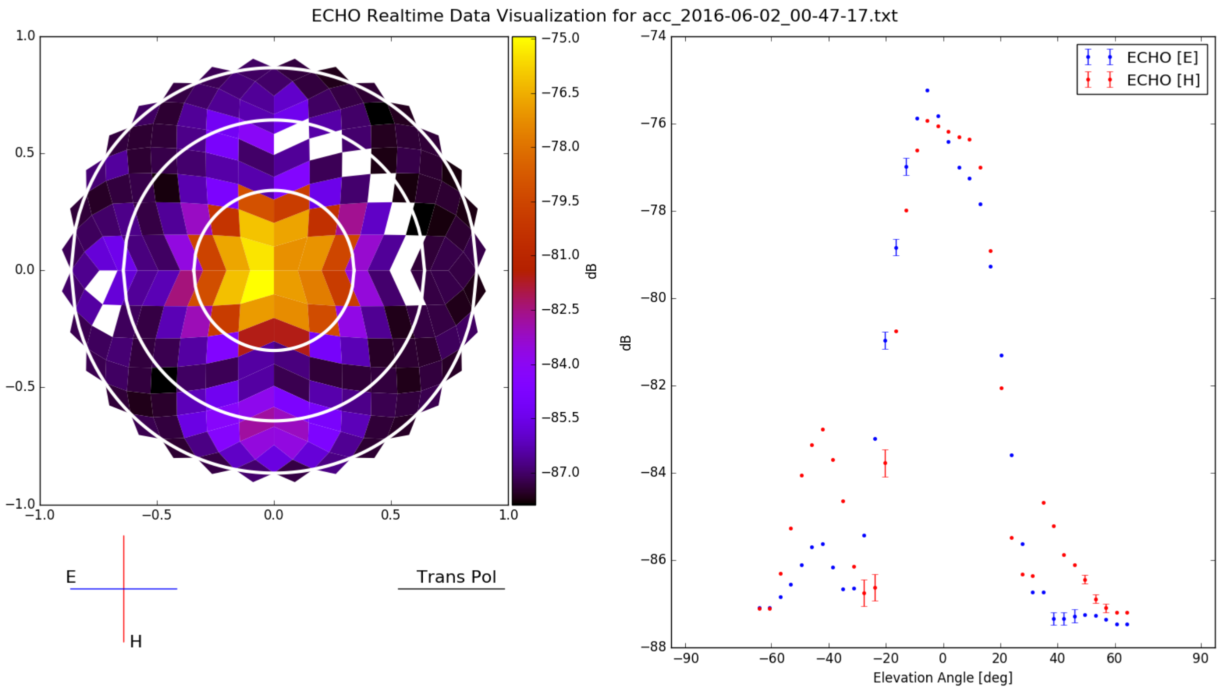
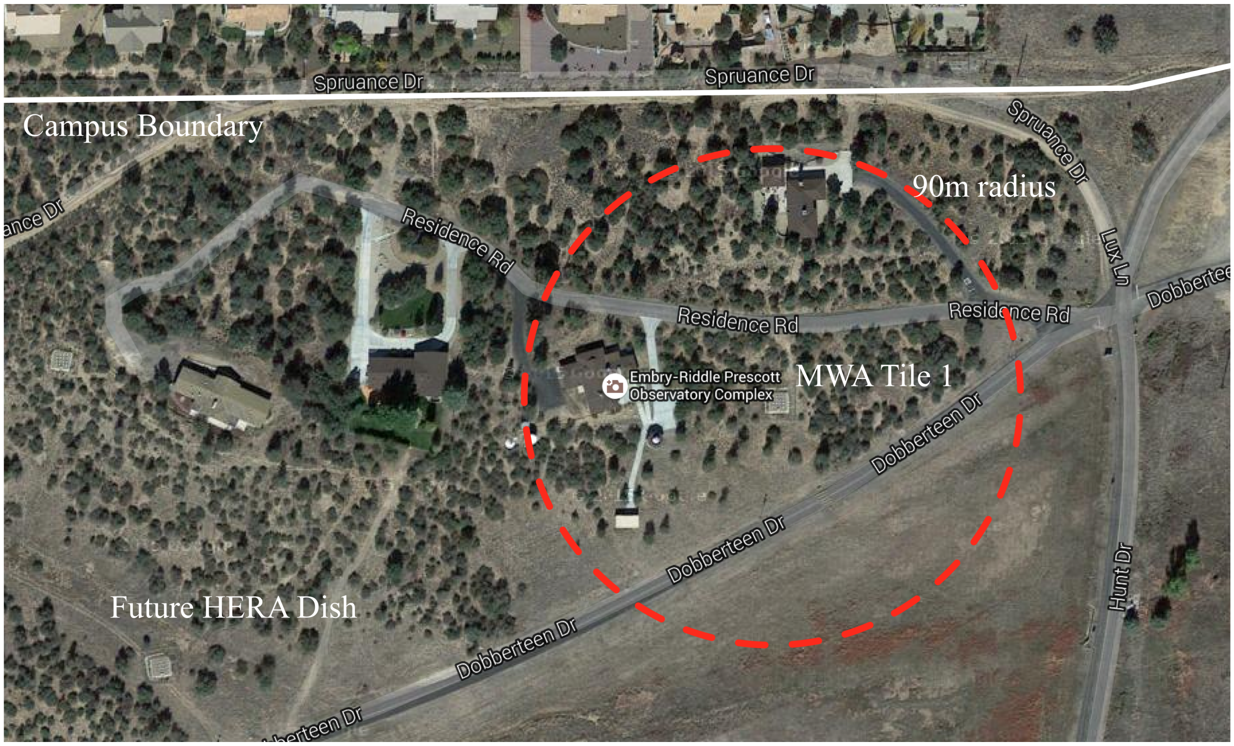
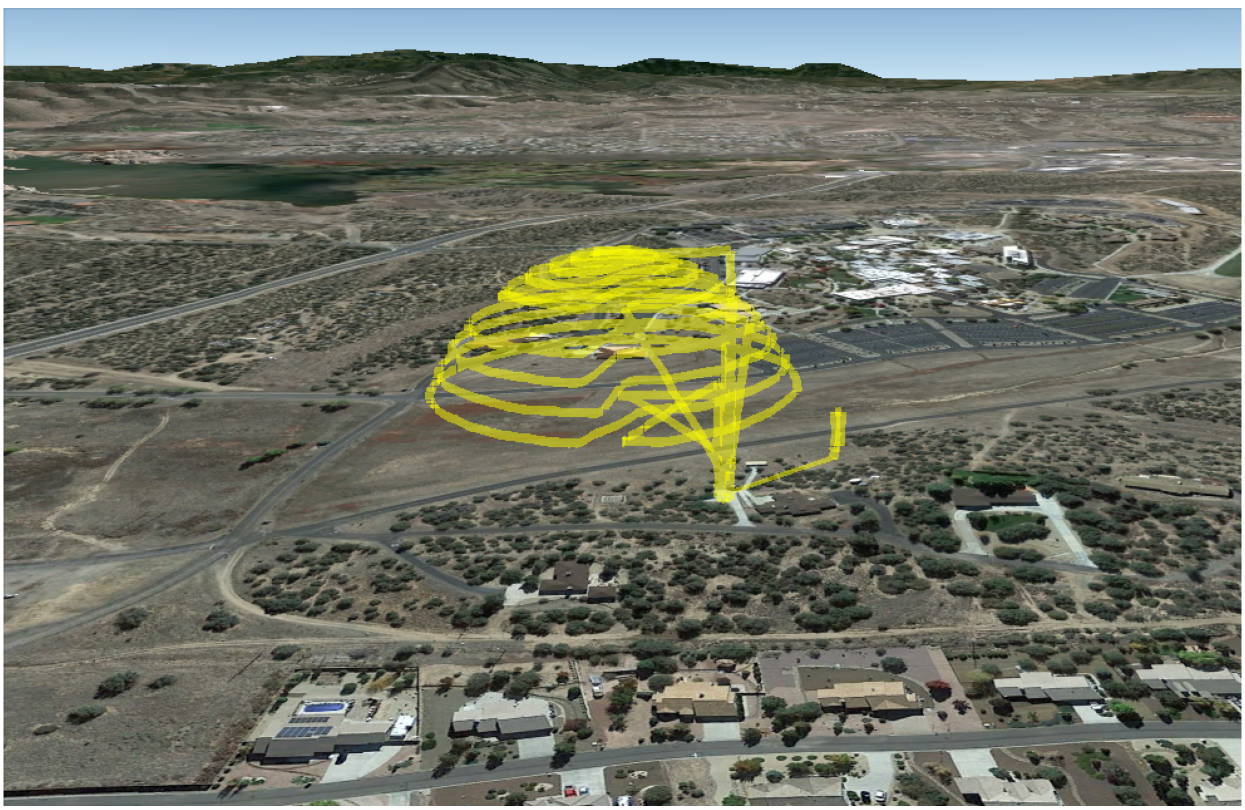


Figure 2: Here, we can see the square sin(x)/x structure expected from a square phased array aperture. Some data points are missing because of incomplete flight coverage. The gain towards the southern side-lobe is higher than the northern and there is a noticeable east-west slope across the main lobe of the beam. These features are likely associated with the fence surrounding the tile.

Flight operational considerations

The ERAU observatory is located 1.5 miles away from the local airport which services a small number of commercial flights, forest service, and the Embry Riddle flight school which is its most frequent user. UAS operations on the ERAU campus are allowed during daylight hours and below 300ft after informing the airport tower control. The flight path and operational procedures were reviewed in consultation with the ER Safety Officer. A flight plan was agreed that kept to a flight ceiling of 90m (295ft) and a radius of 295ft.





Above is an aerial view of the Embry Riddle Observatory. MWA tile and maximum flight operations radius of 90m are shown in the top photo. A visualization of one MWA tile mapping flight over the Embry Riddle Observatory is shown in the bottom panel. The drone follows waypoints arranged to sample the sphere uniformly but limited conservatively to a minimum altitude of 60m. Future flights will add lower altitude levels to the 20m level.

Student Involvement

A principle focus for the ECHO project is to provide opportunities for undergraduates to have a hands-on science research experience. Since 2014, eleven students have been members of the ECHO program, contributing to all areas in all aspects of the project including design, construction, field work, and data analysis. Students are given wide latitude within their areas of focus to explore solutions under direction by a postdoc through multiple hours per week of direct interaction time. During these times, students receive training in areas such as software development, data analysis, electronics, experimental method, and astronomy while contributing to a significant research project. A large fraction of the student team has worked in the field at the NRAO site at Green Bank, WV and the Embry Riddle Observatory site in Prescott, AZ.

Students

Michael Busch - Data acquisition- Graduated ASU SESE 2016, Pursuing Astro PhD at Johns-Hopkins
Jacob Burba - Data analysis, systems - Graduated ASU Physics 2016, Pursuing Physics PhD at Brown
Lauren Turner - E&M Simulation, Data analysis - Senior ASU SESE
Kali Johnson - Flight operations - Junior ASU SESE
Reid Landeen - E&M Simulation - SESE Staff
Mason Denney - Electrical Design - Graduated ASU SESE 2016
Jay Allison - Acquisition Software - Graduated ASU SESE 2015, Raytheon
Benjamin Stinnett - Drone design and flight, Graduated ASU SESE 2015, Aurobot
Victoria Serrano - Antenna design, laboratory testing, ASU Engineering Masters, 2016
Jose Chavez - Antenna design, electronics testing, Graduated ASU SESE 2014, IBM
David Nelson - Drone testing, system design, 1991-2014

Part of the ECHO team poses with an LWA antenna and the ECHO drone on the May, 31 trip to Embry Prescott, AZ. Left to right: Lauren Turner, Jacob Burba, Prof. Andri Gretarsson (ERAU), and Dr. Daniel Jacobs (ASU)

Left to right: Victoria Serrano, Marc Leatham, Mason Denney, Michael Busch build a test interferometer array on the ASU athletic field. (January 2015)

Left to Right: Ben Stinnett, Jacob Burba, and Lauren Turner make adjustments to the ECHO transmitter on location in Green Bank, WV (August 2015).

Left to Right: Marc Leatham, Michael Busch, Jacob Burba, Dr. Daniel Jacobs and Lauren Turner gather to inspect the output of a new lab instrument.

Additional Relevant Developments

Advanced Position Sensing

A principle factor in the accuracy of the beam map is the position and orientation of the drone/transmitting antenna. Position is measured to meter scale precision with the onboard GPS, however the orientation rely primarily on magnetic compasses which are subject to interference by the high currents in the drone. We have partnered with SySense, Inc. a sensor and navigation company in El Segundo, CA to prototype an attitude measurement sensor which uses differential GPS receivers mounted on a boom to provide an absolute measurement of the angle of the calibration transmitter antenna. SySense is developing new technology which makes this differential measurement more robust to use in operation systems and is motivated to acquire field test data. Under the current agreement, SySense will build a prototype test unit to be used as part of the ECHO system. To date, a preliminary design has been reached, data formats have been specified, and the prototype is currently under construction for test in late summer 2016.

Open Design

Experimental low frequency astronomy is a rapidly growing field around the world, with a large number of potential users of the ECHO system, far more than can be served directly by any group. To better serve this community we have made it our goal for ECHO to be a completely Open Source project and to assist groups around the world in making their own local ECHO system. Beam mapping software is available on github at https://github.com/dannyjacobs/ECHO, documentation at http://dannyjacobs.github.io/ECHO and an email list https://groups.google.com/d/forum/astro_ECHO.

Partners

- Though ECHO is an independent project intended for general use across the community we are closely affiliated with the Hydrogen Epoch of Reionization Array (HERA) project. Our next goal is to map the beam of HERA's 14m transit dishes. The ASU team has partnered with Embry Riddle to build a dish specifically for this purpose in Prescott Arizona. Dish construction has commenced and is targeting completion before the end of this summer. (A. Gretarsson, EARU)

- The ECHO team has advised in the construction of an ECHO system to map beams of the HIRAX array 21cm baryon acoustic oscillation array currently under development adjacent to HERA. (C. Chang and B. Saliwanchik at University of Kwazulu-Natal)

Citations

Neben, A.R., Bradley, R.F., Hewitt, J~N. et al., *Measuring phased-array antenna beampatterns with high dynamic range for the Murchison Widefield Array using 137 MHz ORBCOMM satellites*, Radio Science, 2015, 50, 614-629

Sutinjo, A., O'Sullivan, J., Lenc, E., Wayth, R.~B., Padhi, S., Hall, P., Tingay, S.J., *Understanding instrumental Stokes leakage in Murchison Widefield Array polarimetry,* Radio Science, 2015, 50, 52-65

Thyagarajan, Nithyanandan, Jacobs, Daniel C., Bowman, Judd D., Barry, N., Beardsley, AP., Bernardi, G. et al. *Confirmation Of Wide-Field Signatures In Redshifted 21 Cm Power Spectra* The Astrophysical Journal Letters, 807, L28, 2015

Thyagarajan, Nithyanandan, Jacobs, Daniel C., Bowman, Judd D., Barry, N., Beardsley, AP., Bernardi, G. et al. *Foregrounds In Wide-Field Redshifted 21 Cm Power Spectra* The Astrophysical Journal, 804, 14, 2015